Dual Phase Soft Magnetic Laminates for Low-cost, Non/Reduced-rare-earth Containing Electrical Machines

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GE Global Research

Annual Merit Review and Peer Evaluation
June 20th, 2018

Project ID# elt090

Imagination at work.

Project Overview

Timeline

- Project start date: October 2016
- Project end date: September, 2019
- Percent complete: 50%

Budget

- Total project funding: $6,848,335
  - DOE: $4,999,285
  - Contractor: $1,849,050
- FY 2017 Funding
  - $2,557,127
- FY 2018 Funding
  - $2,226,115

Partners

- GE Global Research
- Oak Ridge National Laboratory
- UQM Technologies, Inc.
- Carpenter Technology Corporation

Barriers addressed

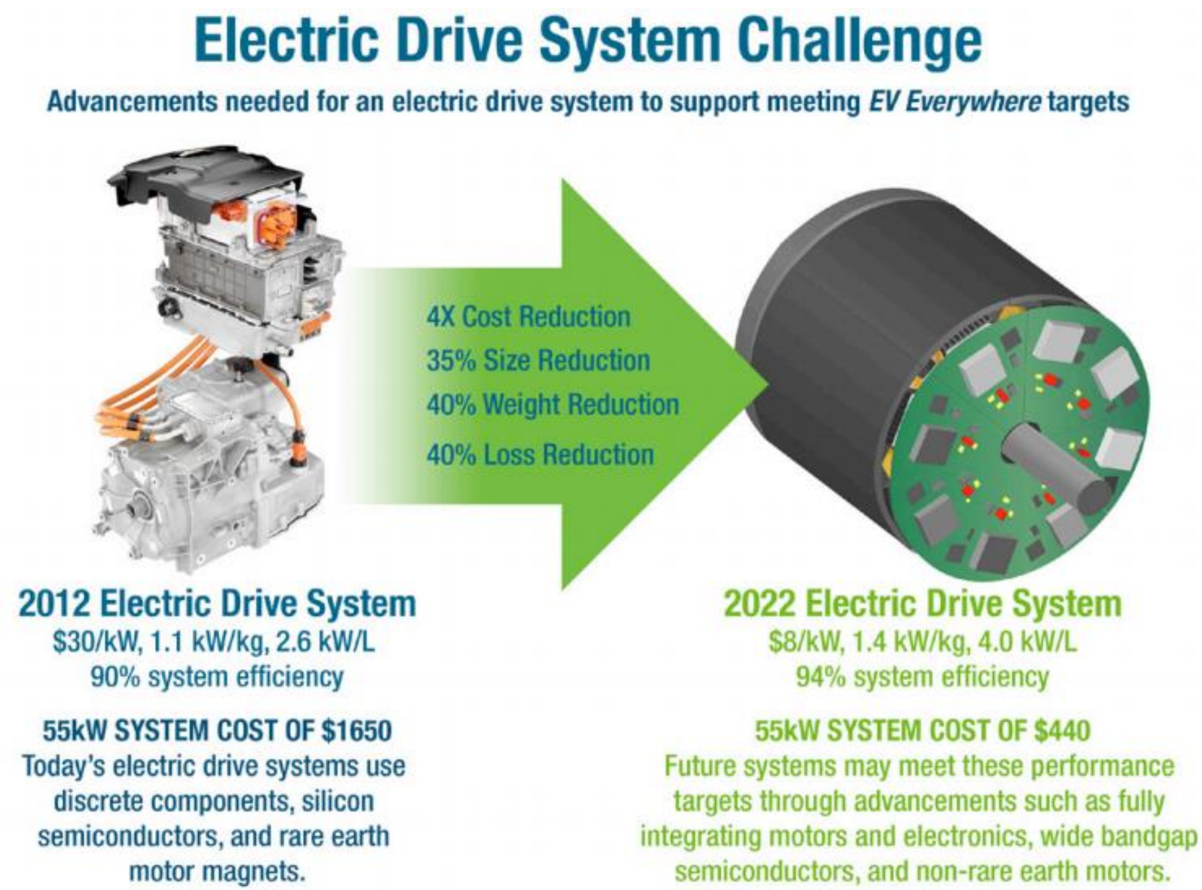
- Cost of Materials and Components
- Component Volume and Efficiency
- Component Weight

Targets

Parameter	Target
Peak Power (kW)	≥55
Continuous Power (kW)	≥30
Specific Power (kW/kg)	≥1.6
Power Density (kW/l)	≥5.7
Maximum Speed (rpm)	14,000
Maximum Efficiency (%)	≥96
Cost ($/kW)	≤4.7

Relevance

- Low-cost, high-performance advanced traction motor: key enabler to meeting the 2022 EV Everywhere targets for the electric traction system
- Elimination of rare-earth permanent magnets: enhance the sustainability of the critical materials supply chain.



Relevance: Objectives

- The project goal is to demonstrate scaled-up manufacturing of the dual phase magnetic materials and demonstrate a full-scale traction motor capable of meeting these targets:

Parameter	Target
Peak Power (kW)	≥55
Continuous Power (kW)	≥30
Specific Power (kW/kg)	≥1.6
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Maximum Speed (rpm)	14,000
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Cost ($/kW)	≤4.7

- From March 2017-March 2018, the objectives were:
  - Produce 1,000 lbs of 0.010” thick by 11” wide dual phase alloy
  - Calculate 20% increase in performance in dual phase motor design

Relevance: Barriers

Dual phase materials allow synchronous reluctance motors to have same *component weight and volume* and *efficiency* as internal permanent magnet motors

Performance – Preliminary EM design Full Scale

Parameter	Target	Calculated (48 slot design)	Remarks
Peak Power (kW)	≥55	56.2	
Continuous Power (kW)	≥30	34	
Specific Power (kW/kg)*	≥1.6	1.93	For peak power operating point
Power Density (kW/l)	≥5.7	5.86	Not including Cooling jacket
Maximum Speed (rpm)	14,000	14,000	
Maximum Efficiency (%)	≥96	**95.3**	Still to be optimized based on: • winding design and loss data • compromise between Avg. torque and torque ripple

Relevance: Barriers

- Dual phase synchronous reluctance use no rare-earth permanent magnets
- Raw material cost is reduced by 26%

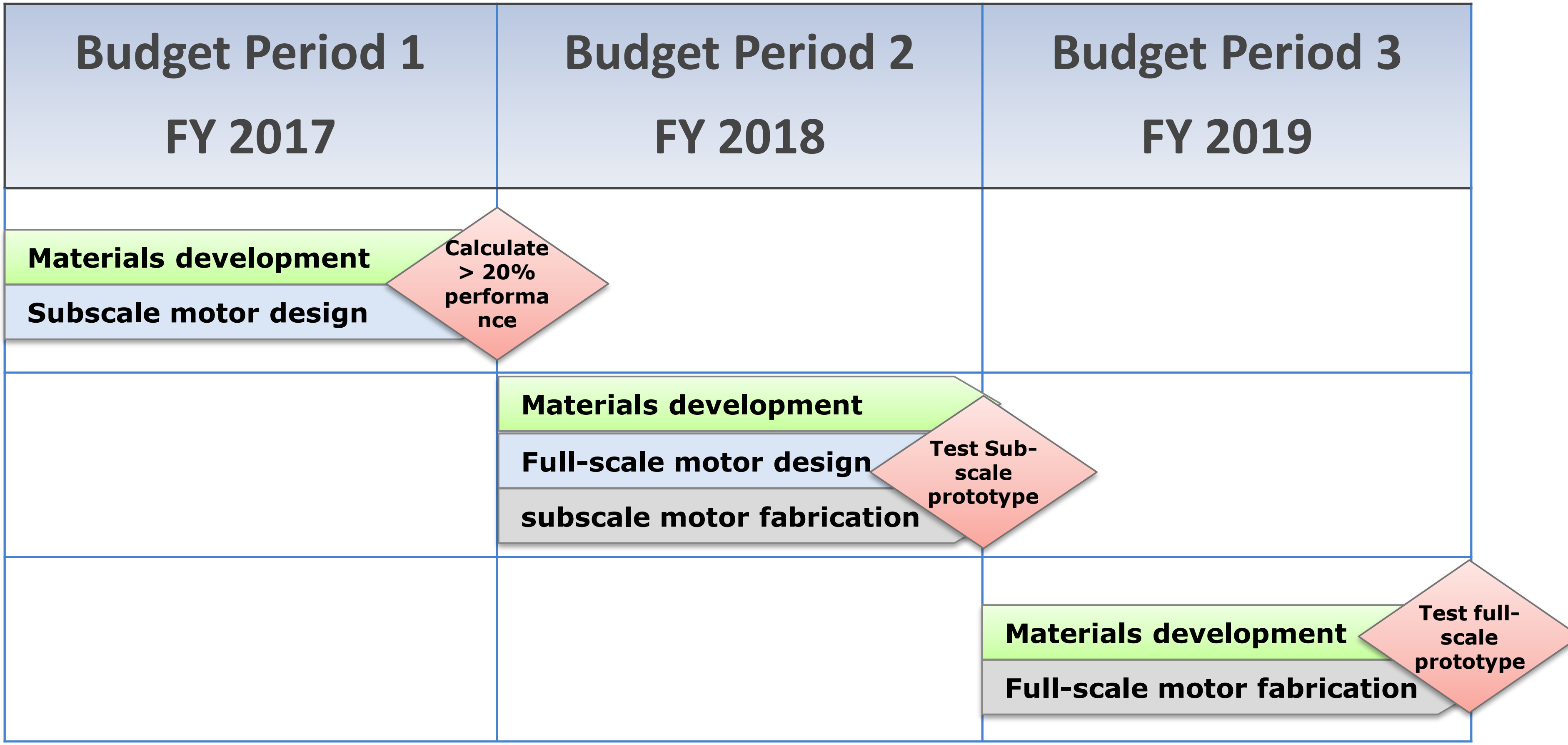
(All costs in 2018 dollars.)

Active Component	2010 Prius IPM [1,2]			Dual Phase Rotor SynRel		
	Mass (kg)	Cost	$/kg	Mass (kg)	Cost	$/kg
Rotor	6.7	$15.41	$2.30	4.9	$22.54	$4.60
Stator	10.4	$23.92	$2.30	13.0	$29.90	$2.30
Magnets	0.8	$61.60	$77.00	--	--	--
Copper	4.9	$33.57	$6.85	10.6	$72.61	$6.85
Total	22.8	$134.50	$5.90	28.5	$125.05	$4.39

[1] R. H. Staunton et al., "PM Motor Parametric Design Analyses for a Hybrid Electric Vehicle Traction Drive Application," Table 7.2, ORNL TM-2004/217.
[2] T. A. Buress et al., "Evaluation of the 2010 Toyota Prius Hybrid Synergy Drive System," Table 2.7, ORNL/TM-2010/253.

- Elimination of rare earth magnets enables 26% active material cost reduction
- Active raw material cost $2.3/kW at 55 kW peak power, *not including shaft and bearings*
- Target is ≤$4.7/kW, allowing margin for dual phase manufacturing cost uncertainty
- Cost of manufacturing components to be addressed during scale up after prototype demonstration

Approach: Milestones



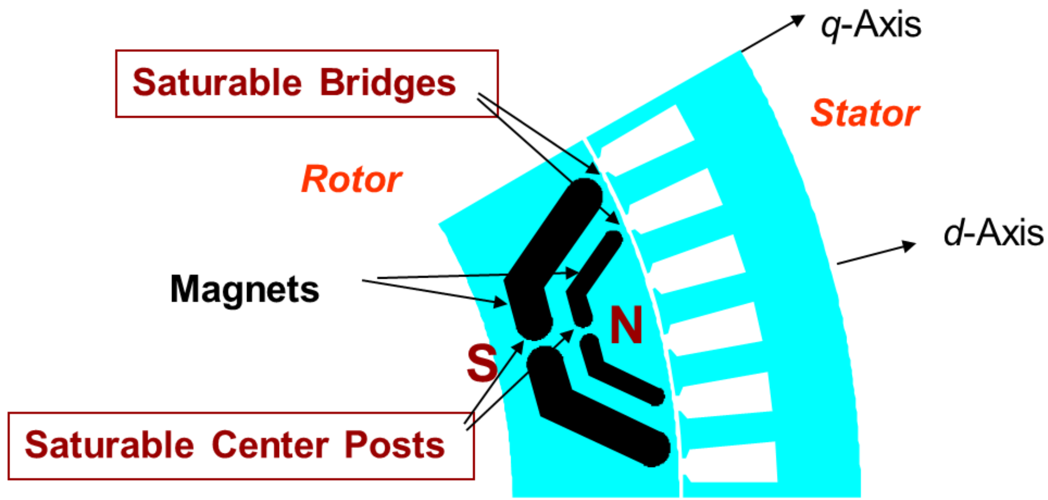
Go/NoGo Decision Point

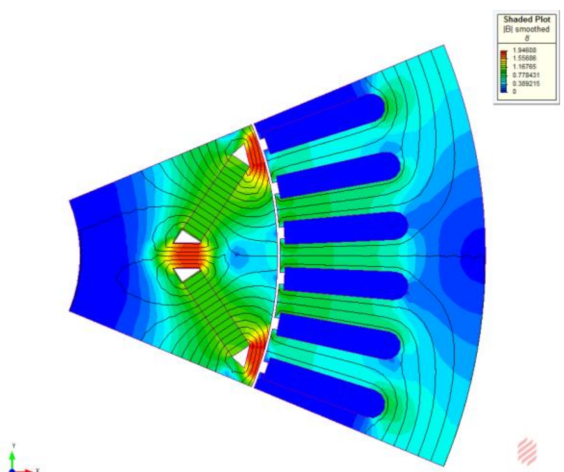
Approach: Milestones

Milestones	Description	Planned Completion Date
Produce 275 kg of 20.3 cm wide by 254 µm thick sheet	Dual phase magnetic laminate material is produced as rolled alloy sheet	3/31/17
Report nitride kinetics study and residual stress analysis on 2.5 cm by 5.0 cm coupon	Complete analysis of nitrogen diffusion into dual phase alloy	6/30/17
Complete initial market study	Determine target market and competitors	9/30/17
Detailed subscale dual phase design shows 20% greater performance than conventional rotor	Project review at end of BP 1 will review completed electromagnetic, thermal and mechanical performance of detailed subscale design	9/30/17
Nitride laminates for 13.9 cm dia. by 13.3 cm length subscale prototype.	Produce sufficient quantity nitrided 13.9 cm dia. laminates to manufacture a rotor 13.3 cm long	12/31/17
Stacked and bonded subscale rotor with 13.3 cm stack length	A stacked and bonded rotor assembly is made from the nitrided and cleaned subscale laminates	3/31/18
Report nitride kinetics study and residual stress analysis on 13.9 cm dia. subscale laminate	Complete analysis of nitrogen diffusion into nitrided laminate of subscale prototype	6/30/18

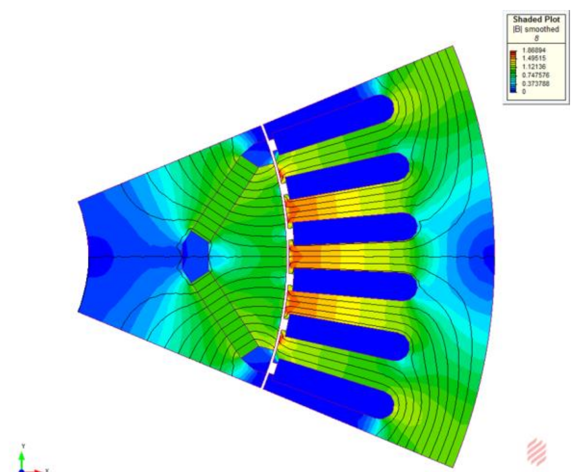
Approach: Strategy

- Electric machine designers wish for local control of magnetic permeability in rotors to increase power density and efficiency
- Reluctance-torque machines with non-magnetic bridges and center posts show clearest benefits
- Other material solutions exist but with unfavorable balance of properties





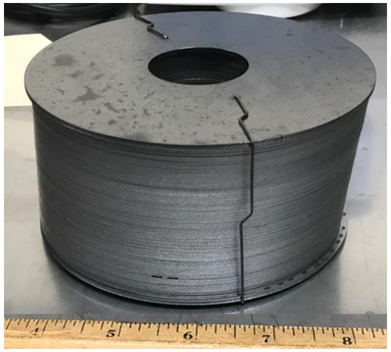
magnetic posts and bridges



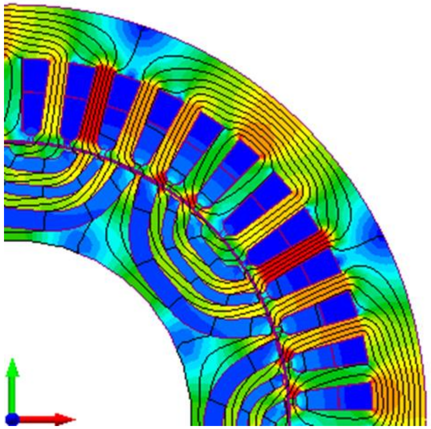
non-magnetic posts and bridges

Approach: Plan

- FY2017
  - Produce 1,000 lbs of custom dual phase alloy sheet
  - Measure material properties and calculate motor performance
- FY2018
  - Build and demonstrate subscale motor prototype
  - Improve manufacturing process to achieve better control of material properties
  - Demonstrate that tested performance matches calculated performance
- FY2019
  - Build 55 kW peak power dual phase SynRel prototype
  - Demonstrate that dual phase SynRel motor constructed without permanent magnets can match or exceed performance of IPM motor

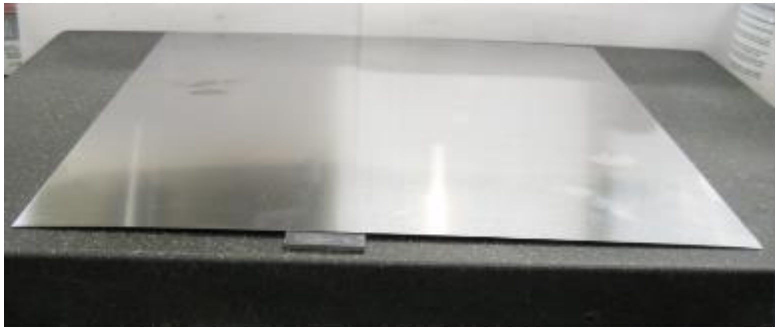


Cut laminates for sub-scale prototype from sheet



Technical Accomplishments & Progress

Custom alloy sheet

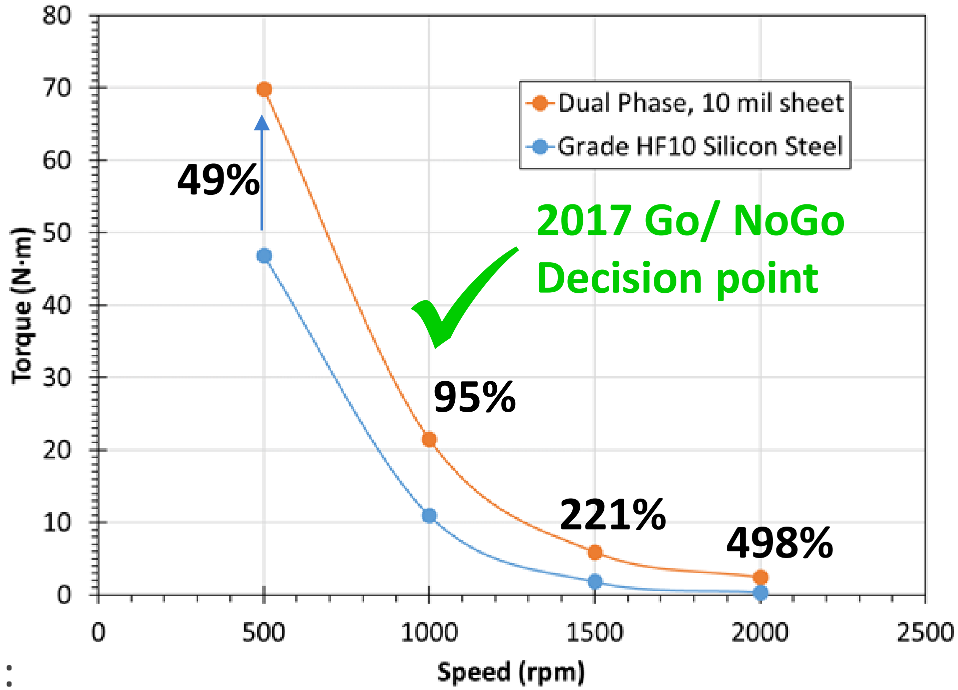


Sample size	11”x 0.5”
# of sampling locations	15
# of measurements per sampling location	3
Thickness	0.0098±0.0001

- 1,000 lbs W11”xT0.01” sheet produced to GE’s spec. by Carpenter Technology Corp.
- Comprised of magnetic phase of dual phase alloy
- Met or exceeded all magnetic, chemistry, and dimensional requirements
- To be used to fabricate the rotors of both dual phase motor prototypes

Technical Accomplishments & Progress

Calculated subscale prototype performance



From SOPO:

Milestone	Type	Description
Detailed subscale dualphase design shows 20% greater performance than conventional motor	Go/No Go	Project review at end of BP 1 will review completed electromagnetic, thermal, and mechanical performance of detailed subscale design

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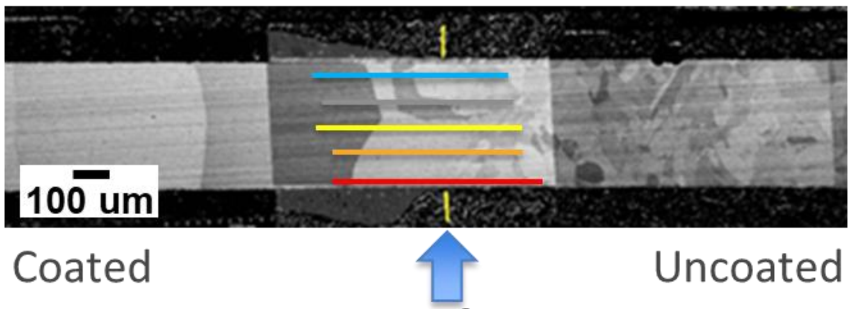
Technical Accomplishments & Progress

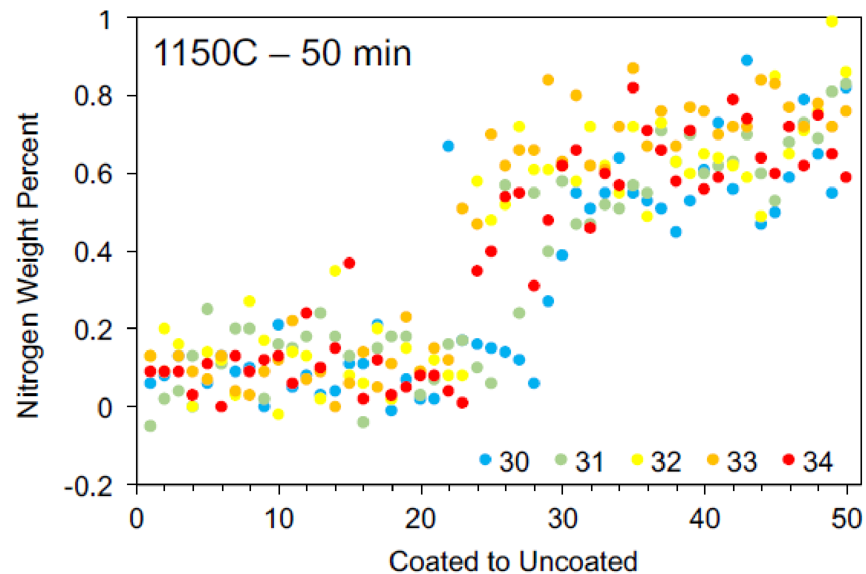
Nitrogenation kinetics

Nitrogenated at 1,150 °C for 50 minutes



Coated Uncoated

Interface

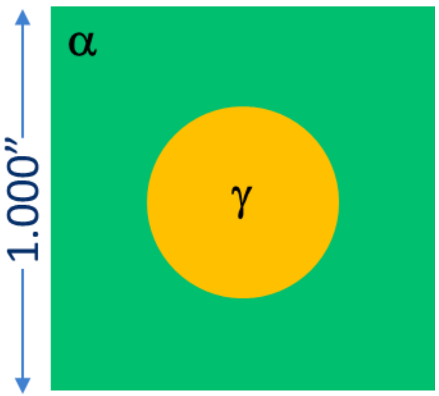


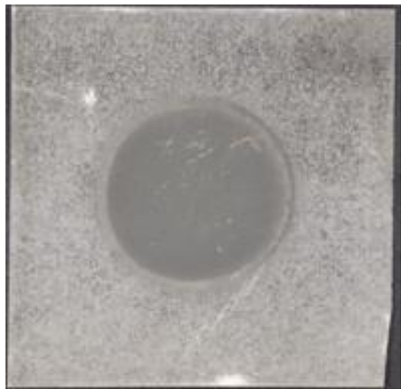
- Series of heat treatment studies on coupons at Oak Ridge National Lab
- Rate limiting step is phase transformation of ferrite to austenite
- Nitrogen was not observed to have diffused ahead of phase boundary
- Local environment in furnace has effect on nitrogen absorption rate

Technical Accomplishments & Progress

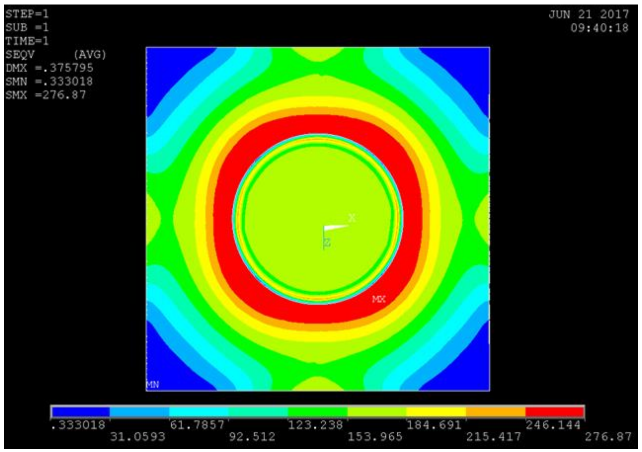
Residual stress analysis

Differential CTE between magnetic (α) and non-magnetic (γ) phases leads to residual stress and warping after heat treatment



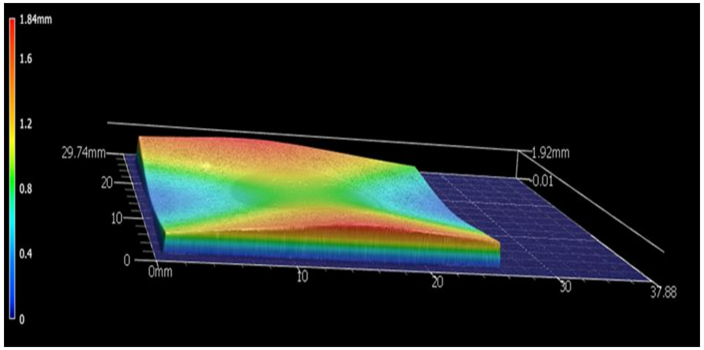


Heat treated dual phase coupon



Calculated Von-Mises stress distribution

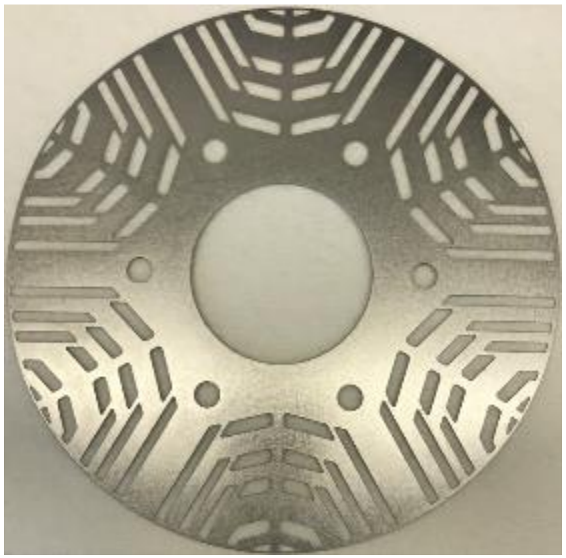
- Stress and warpage degrade magnetic permeability due to magnetostriction.
- Leads to lower than expected torque output.
- Synchrotron transmission XRD techniques being explored with ORNL to directly measure stress.



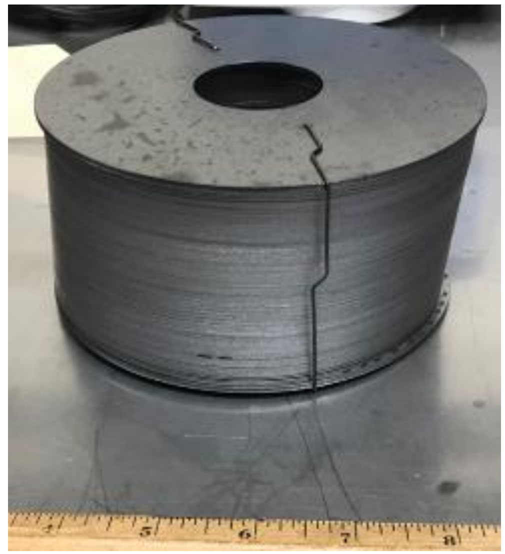
Optically measured deflection in heat treated coupon

Technical Accomplishments & Progress

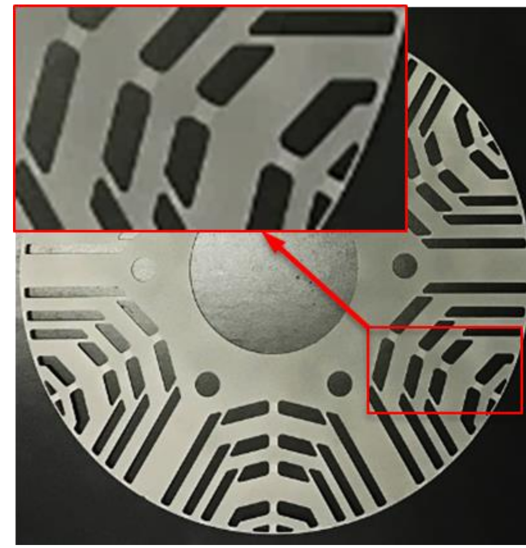
Dual phase laminate manufacturing



As-cut single phase laminate



As-cut stack of laminates



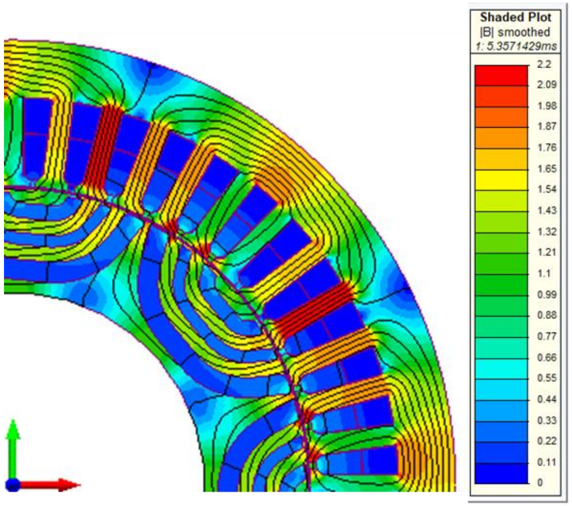
dual phase laminate

- Sub-scale rotor laminate design completed
- 1,500 laminates produced for process development and subscale prototype
- Approximately 550-600 required for prototype rotor
- Dual phase laminates manufacturing underway

Technical Accomplishments & Progress

Motor development - 30 kW Full-scale prototype

Parameter	Target	Calculated
Peak Power (kW)	≥55	56.2
Continuous Power (kW)	≥30	34
Specific Power (kW/kg)*	≥1.6	1.93
Power Density (kW/l)	≥5.7	5.86
Maximum Speed (rpm)	14,000	14,000
Maximum Efficiency (%)	≥96	95.3
Cost ($/kW)	≤4.7	tbd



30 kW Dual Phase design with non-magnetic bridges @ 55 kW operation

- Preliminary electromagnetic design completed
- Two-layer synchronous reluctance design
- Active materials only, mass does not include cooling jacket
- Design is still to be optimized on:
  - Winding design and loss data
  - Compromise between average torque and torque ripple
- Mechanical and thermal design to be completed in 2018

Responses to previous year reviewers' comments

- This project was not reviewed last year.

Collaboration and co-ordination with other institutions

OAK RIDGE National Laboratory

- Expertise in nitriding/nitrogenation
- Measurement of nitrogenation kinetics
- X-Ray/Neutron residual stress distribution

UQM TECHNOLOGIES

- UQM Technologies is a sub-contractor
- Building sub-scale and full-scale prototypes
- GE is providing dual-phase rotor

CARPENTER®

- Carpenter Technology Corp. is a vendor
- Producing custom alloy dual phase sheet to GE's specification

Remaining challenges and barriers

Challenge	Mitigation plan
Ceramic mask application method used to define non-magnetic regions may not be scalable due to low rate of application	Alternate method using thermally-grown oxide under development and may be chosen to manufacture full-scale prototype
Trade-off between mechanical and magnetic properties not fully explored	DOE in process to develop processing-property relationship using scalable production methods
Assembled rotor permeability reduction due to magnetostriction	Reduce laminate warpage by optimization of motor design and laminate processing parameters

Proposed future research

- FY2018
  - Complete fabrication and testing of 3.7 kW sub-scale prototype
  - Develop processing/property relationships for dual phase materials
  - Complete full-scale prototype design

- FY2019
  - Produce dual phase rotor laminates for full-scale 55 kW prototype
  - Manufacture full-scale 55 kW prototype
  - Test full-scale 55 kW prototype

Any proposed future work is subject to change based on funding levels

Summary

- 1,000 lbs of dual phase alloy produced
- Manufacturing process control improved
- Calculated dual phase motor performance exceeds that of motor fabricated from silicon steel
- Sub-scale prototype being fabricated
- Preliminary full-scale prototype performance estimates:

Parameter	Target	Calculated (48 slot design)	Remarks
Peak Power (kW)	≥55	56.2	
Continuous Power (kW)	≥30	34	
Specific Power (kW/kg)*	≥1.6	1.93	For peak power operating point
Power Density (kW/l)	≥5.7	5.86	Not including Cooling jacket
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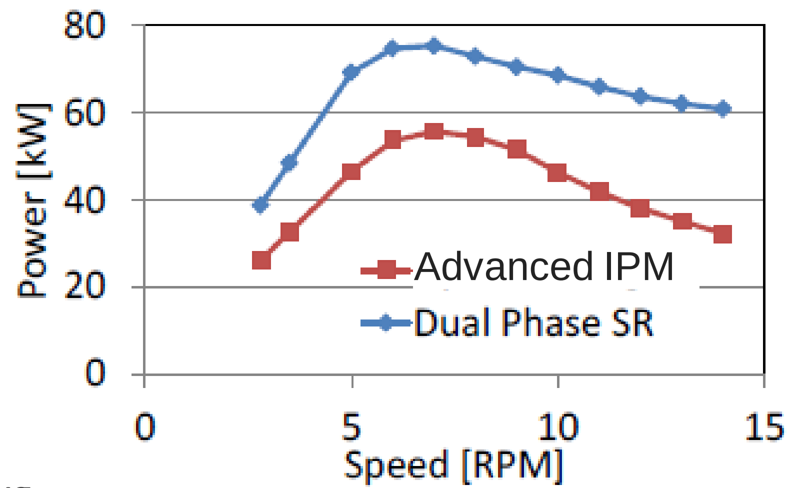
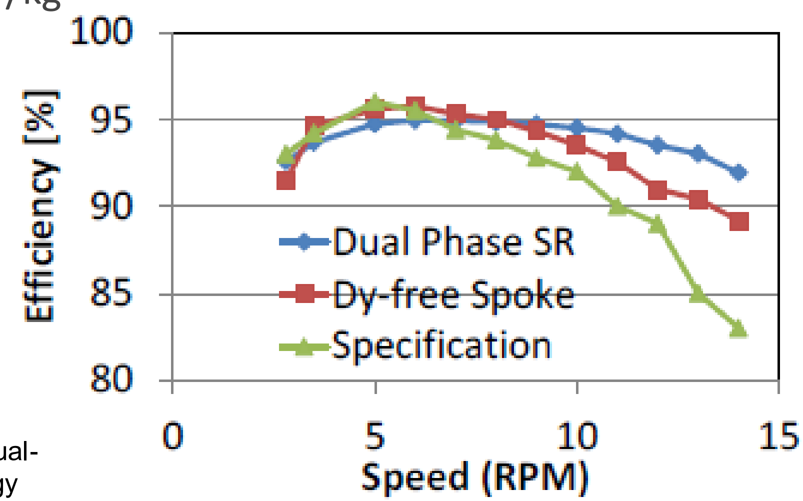
Technical Back-Up Slides

Dual phase laminate advantage

(Completed on project DE-E0005573, “Alternative High-Performance Motors with Non-Rare Earth Materials”, 2012-2017)

Item	Dual phase SynRel	Advanced IPM	
Poles	12	8	
Layers	2	-	
Stack length	54.4 mm	30.5 mm	
Magnet mass	0	1.14 kg	
Active mass	24.9 kg	23.7 kg	
Stator OD	288 mm	326 mm	
Air-gap diameter	199.3 mm	193.5 mm	
Rotor ID	121.2 mm	110 mm	**Target**
Power Density	**2.43 kW/kg**	2.55 kW/kg	≥ 1.6 kW/kg
Peak power at TCP	**60.4 kW**	60.5 kW	≥ 55 kW
Saliency at peak power	3.31	1.38	
Power at 14k	**32.2 kW**	33 kW	≥ 30 kW
Saliency at 14k	3.63	1.91	
Efficiency at TCP	93.3%	91.4%	
Efficiency at 14k	90.3%	89.2%	

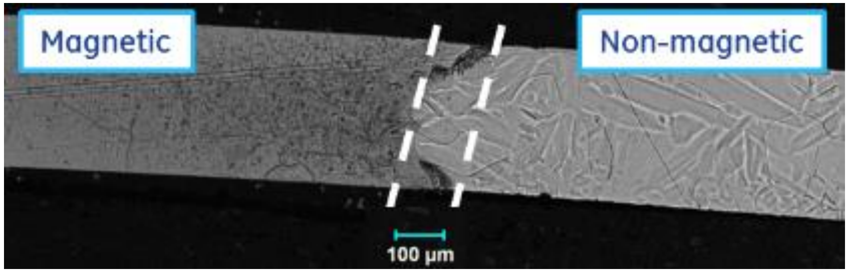




P. B. Reddy et al., “Design of Synchronous Reluctance Motor Utilizing Dual-Phase Material for Traction Applications,” Proceedings of the 2015 Energy Conversion Congress and Exposition, p. 4812-4819.

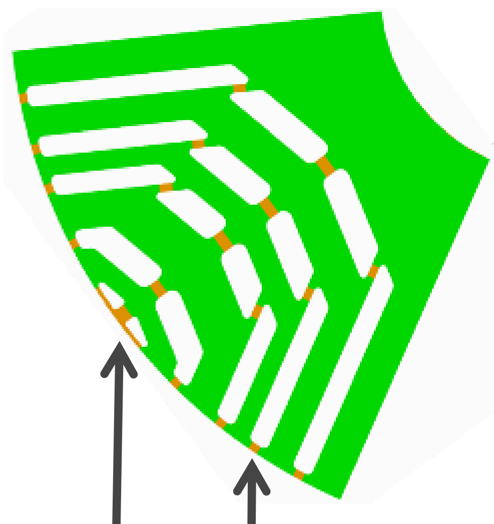
Dual phase soft magnetic laminates

(Completed on project DE-E0005573, “Alternative High-Performance Motors with Non-Rare Earth Materials”, 2012-2017)

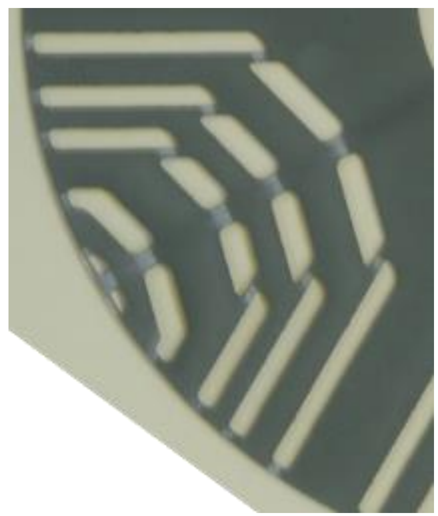


Cross section of interface between magnetic and non-magnetic regions

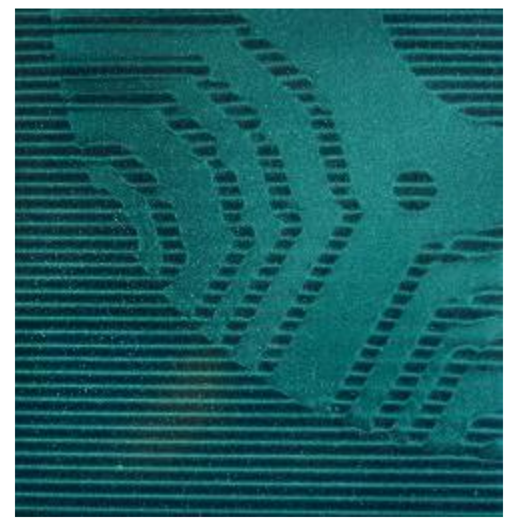
- Alloy and process developed for laminates with locally controllable magnetization
- This enables electric motors and generators with increased power density and efficiency



Non-magnetic bridges and posts patterned into motor laminate



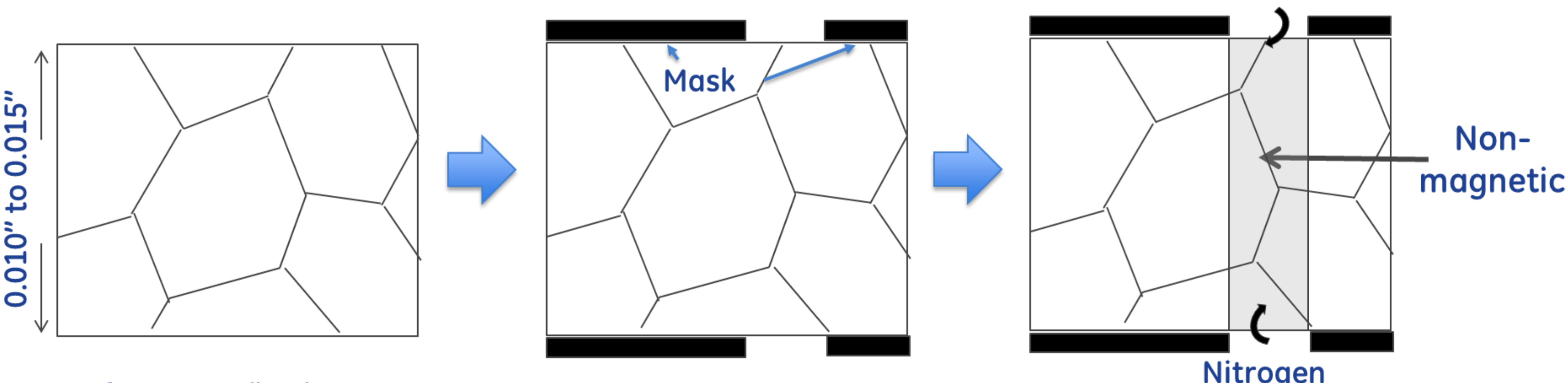
Lithographic process used to define non-magnetic regions



Stripe domain pattern shows through non-magnetic bridges and post

Dual phase soft magnetic laminates
Processing method

- **The Fe-Cr-Mn alloy can be produced as fully magnetic rolled sheet (as thin as 0.010”)**
- **A novel lithographic process is used to define the regions to be made non-magnetic with a mask**
- **Heat treatment in nitrogen is used to transform the exposed regions into the non-magnetic state**
- **Chemical and/or mechanical methods used to remove mask**



Soft-magnetic alloy sheet in the fully magnetic condition

Lithographic mask applied to define magnetic and non magnetic regions

High temperature nitriding stabilizes non-magnetic phase

US Patent # 9,634,549, issued April 25, 2017